APPLICATION OF RISK MANAGEMENT TECHNIQUES TO ROAD DISASTER MANAGEMENT

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ABSTRACT

We developed a practical road disaster management procedure for various natural disasters by applying risk management techniques. The risk is herein defined as a product of likelihood of disastrous event and its consequence. The road facilities targeted are bridges, embankments, tunnels, slopes, and so forth, and various natural disasters such as earthquakes, tsunamis, heavy rainfalls and floods are incorporated into analysis. We assume both direct and indirect damage in the present study. The former includes human damage and restoration cost of damaged facility, and the latter includes economic loss associated with detouring and stranded communities. A particular emphasis is put on rating the risks due to different natural disasters over various road facilities by common indices. Based on the proposed procedure, we performed a case study for a 110km section of a national highway running along the Pacific coastline of Japan. This section of the highway is comprised of various kinds of road facilities, and the area where the highway passes through has high seismicity and has suffered from typhoons and resultant slope disasters. The results of case study are presented in the form of risk curve, risk register table and risk treatment plan, which is readily applicable to road disaster management.

1. INTRODUCTION

It would seem that the concept of "risk" or "risk management" has recently been introduced to the social and economic fields in addition to the industrial fields. Meanwhile the risk management techniques are less common in the river and road management in Japan, despite a fact that rivers and roads are exposed to many risks, such as earthquakes and heavy rainfalls and so many others even only from natural disasters. The authors assume that this is because management of social assets such as rivers and roads deals with disasters in ways different depending on the type of disaster and those disasters have been managed less often in an integrated manner as they are mainly responded individually. Another reason would be that judgment on the level of danger or determination of the priority of measures for a certain disaster has mainly been based on the past experience.

There are, however, cases somewhere outside Japan where risk management techniques are actually applied to road disaster management. Take New Zealand for instance. They have an established set of risk management procedures or the Risk Management Process Manual [1], which is applied to their road management practice. This manual was published by the Transit New Zealand that is responsible for the stewardship New Zealand's state highways, and it has the following features:

1) Threat (an event that has the potential to move the outcome of an activity to a more unfavorable position) as well as opportunity (an event that has the potential to move the outcome of an activity to a more favorable position) are considered as risks.
2) A risk is measured in terms of a combination of the likelihood of an event and its consequences, where the likelihood of an event and its consequences are rated to allow quantitative evaluation of risks for various road facilities against various disasters.

In the present study we applied the concept of Transit New Zealand's Risk Management Process Manual to proposing a practical method to systematically evaluate the risk of road facilities by natural disasters. Road facilities included in our study are bridge, embankment, tunnel and slope. Earthquake, tsunami, and heavy rainfall are major natural disasters considered. For damage to road facilities, direct damage and indirect damage are both assumed. In particular, an emphasis is put on evaluating risks of damage to various road facilities due to various disasters by common indices. In examining the priority of road disaster prevention measures, we incorporated the concept of opportunity, which is favorable outcome incidentally resulting from road disaster prevention measures, into analysis. Finally we conducted a case study with the proposed method for an about 110km section of a national highway spanning along the Pacific coastline of Japan. On this target section of the highway, there are a variety of road facilities. Seismicity of the region is high, and disasters by heavy rainfalls such as typhoons have also occurred. In the case study we systematically evaluated the risk of damage to the highway, and based on the evaluation results we examined the priority of road disaster prevention measures, where opportunity was considered in addition to threat.

2. EVALUATION PROCEDURE OF ROAD DISASTER RISKS

2.1 Overview

We propose a practical evaluation procedure for road disaster risks by natural disasters such as earthquakes and heavy rainfalls that frequently occur in Japan, which can be applied to examine the priority of road disaster prevention measures. An outline of the proposed evaluation procedure for road disaster risks is as follows:

1) Identify natural disasters (hazards) that may affect the target area and road. Then, determine if the damage is actually done or not and the damage level by combining vulnerability of each road facility and hazard to evaluate the direct damage to each road facility and the indirect damage attributable to disruption of road traffic. Finally, identify the facility as the damaged facility when it is judged that the damage is to occur (risk identification).
2) For evaluating the impact of each damaged facility, formulate an impact evaluation standard to rate the consequence of damage for quantification. Rate the likelihood of hazard also. Then, evaluate the risk of road facility due to hazard by multiplying the likelihood of hazard and its consequence (risk analysis and evaluation).
3) Develop a menu of disaster prevention measures for road facilities that are judged to require measures, and examine the priority of road disaster prevention measures, in which opportunities that are favorable outcomes incidentally resulting from measures against threats are considered (risk treatment).

Figure 1 shows the proposed procedure of road disaster risk management, and each process is described below.

2.2 Identification of Natural Disasters (Hazards)

Hazards to be considered include earthquake, tsunami, overtopping wave, flood by heavy rainfall and slope disaster by earthquake or heavy rainfall.

2.3 Damage Judgment of Road Facilities

For road facilities on the target section of road, such as bridges, embankments, tunnels and

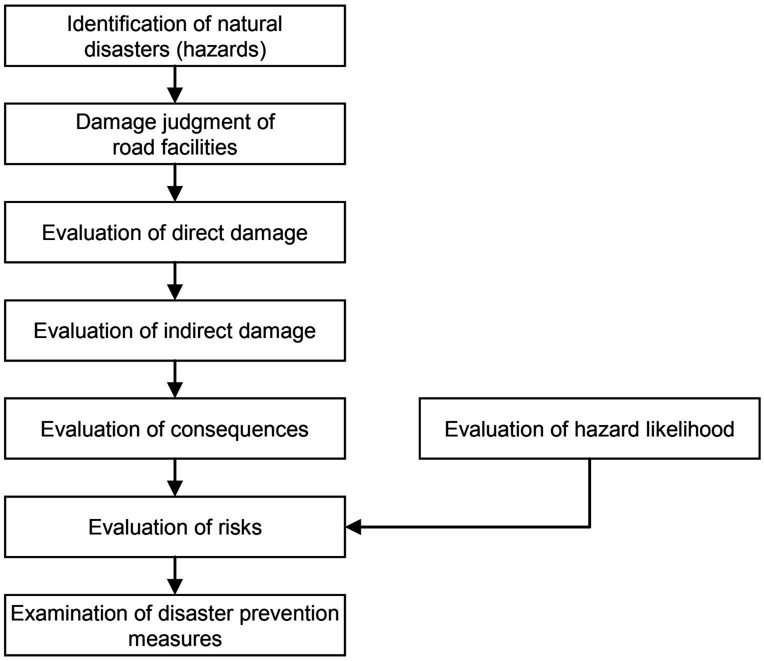

Figure 1 Procedure of road disaster risk management

slopes, determine whether any damage is done by the hazards identified above to each of those facilities and the damage level. We refer to previous research results to establish the methods of damage estimation for individual road facilities due to various hazards.

2.4 Evaluation of Direct Damage

As direct damage we evaluate human damage that is damage to road users and restoration cost of road facilities representing physical damage to road facilities. Regarding the human damage we focus on the damage that may cause fatalities, and as the restoration cost we estimate costs for both emergency repair work and full restoration work of the road facility damaged.

2.5 Evaluation of Indirect Damage

As indirect damage we evaluate the loss by detour traffic and the cost for supporting stranded communities as a result of severed road traffic. For the period during which the indirect damage occur, the period of time from the occurrence of the disaster to the time when the road is restored to the condition available for general traffic by the emergency restoration work is taken into consideration.

2.6 Evaluation of Consequences

We employ a rating technique to evaluate the consequences of disastrous event, which categorizes the impact level based on an impact evaluation standard chart. In our study the impact level for each of the three kinds of damage, i.e., human damage, restoration cost and economic loss (first two are in the scope of direct damage and the third is indirect damage) is categorized into four classes as "major, medium, minor, and none." We rate each class as 10, 5, 1 and 0, respectively, and evaluate the magnitude of consequence by the total of those scores. Table 1 shows the rating of consequences as the basis of evaluation of impact level in this study. The threshold levels are set for each type of damage so that equivalent impacts are assumed among the damage.

2.7 Evaluation of Hazard Likelihood

We employ an annual probability of occurrence of each hazard as hazard likelihood. Hazard likelihood is scored on a scale of 10, 5 and 1 allotted to the level of annual occurrence likelihood as

Table 1 Rating of consequence

Risk	Influence	Rating	Human damage (Fatalities)	Restoration cost	Economic loss
Threat	Major	10	≥1	≥150M yen	≥150M yen or No detour
	Medium	5	<1	50M to 150M yen	50M to 150M yen
	Minor	1		<50M yen	<50M yen
None	None	0	0	0	0
Opportunity	Minor	1		<50M yen	
	Medium	5	<1	50M to 150M yen	
	Major	10	≥1	≥150M yen	

Table 2 Rating of likelihood of hazards

Likelihood	Annual probability of occurrence	Rating
Likely	≥50%	10
Medium	10 to 50%	5
Rare	≤10%	1

Table 3 Number of road facilities

Road facility	Number
Bridge	51
Embankment	17
Slope	89
Tunnel	4
Pedestrian bridge	8
Total	169

"likely, medium, and rare," as shown in Table 2.

2.8 Evaluation of Risks

We evaluate the risk quantitatively by multiplying the likelihood of hazard and its consequence. Both hazard likelihood and consequence are scored as mentioned in the above.

2.9 Examination of Disaster Prevention Measures

We consider both structural and nonstructural measures for the risks that are revealed to need treatment. The priority of measures is then examined based on the cost of disaster prevention measures and the effectiveness of the measures. Evaluation of risks after implementation of measures is made in terms of both threat and opportunity. Applying the concept of opportunity presented in the Risk Management Process Manual of Transit New Zealand, we evaluate the favorable outcomes incidentally achieved from implementation of road disaster prevention measures as opportunities.

3. CASE STUDY ON ROAD DISASTER RISK MANAGEMENT

3.1 Target Area and Route

We performed a case study for an about 110km section of a national highway running through the Pacific coast area of Japan. Along this target section of highway, natural disasters expected to occur include earthquake, tsunami and heavy rainfall. Table 3 summarizes the numbers of road facilities on the target section.

3.2 Damage Judgment

Table 4 shows the combination of hazards and road facilities to be used for damage judgment.

Table 4 Combination of hazards and road facilities

Hazard	Road facility
Earthquake	Bridge
	Embankment
	Approach embankment to bridge
	Slope
	Tunnel
Tsunami	Bridge
	Embankment
	Approach embankment to bridge
	Pedestrian bridge
Heavy Rainfall	Slope
Flood	Bridge
	Embankment
Overtopping	Road

Table 5 Classification of damage

Classification		Remarks
Direct damage	Human damage	Human loss by damage to road facility
	Restoration cost	Cost to restore damaged road facility
Indirect damage	Economic loss	Loss associated with detour and isolated hamlets

Table 6 Pattern of damage occurrence

<table>
<tr><th rowspan="2">Hazard</th><th rowspan="2">Damage level</th><th colspan="2">Direct damage</th><th>Indirect</th><th rowspan="2">Risk evaluation</th><th rowspan="2">Remarks</th></tr>
<tr><th>Human</th><th>Restoration</th><th>Economic</th></tr>
<tr><td rowspan="6">Occurred</td><td rowspan="2">Damage may cause fatalities (Damage Level I)</td><td>Damage</td><td rowspan="2">Damage</td><td rowspan="2">Damage</td><td>Applicable</td><td></td></tr>
<tr><td>No damage</td><td>Applicable</td><td>Precautionary road closure section (Slope x Rainfall)</td></tr>
<tr><td rowspan="2">Damage may cause injuries (Damage Level II)</td><td>Damage</td><td rowspan="2">Damage</td><td rowspan="2">Damage</td><td>Not applicable</td><td></td></tr>
<tr><td>No damage</td><td>Not applicable</td><td>Traffic control (Flood)</td></tr>
<tr><td rowspan="2">No human damage</td><td rowspan="2">No damage</td><td rowspan="2">Minor damage or No damage</td><td>Damage</td><td>Applicable</td><td>Traffic control (overtopping)</td></tr>
<tr><td>No damage</td><td>Not applicable</td><td></td></tr>
<tr><td rowspan="2">Not occurred</td><td rowspan="2">No damage</td><td rowspan="2">No damage</td><td rowspan="2">No damage</td><td>Damage</td><td rowspan="2">Not applicable</td><td>Detour loss</td></tr>
<tr><td>No damage</td><td></td></tr>
</table>

Table 5 lists the direct damage and indirect damage studied.

In the present study, we judge damage with a focus on human damage at each road facility in case a hazard occurs. Such damage is classified into three categories: damage that may cause fatalities (Damage Level I), damage that may cause injuries (Damage Level II), and damage causing no human damage. In principle, we conduct risk evaluation for the kind of damage involving fatalities. Detailed conditions that dictate damage judgment are as follows:

1) Both direct damage (human damage and restoration cost) and indirect damage (detour traffic loss and stranded communities) are evaluated when the damage with Damage Level I occurs, in principle. Refer to the gray areas in Table 6.
2) Neither direct damage nor indirect damage is evaluated in case of damage that may cause no fatalities.
3) Note that no human damage is assumed to occur with a slope disaster by heavy rainfall on the road section with precautionary road closure, however, if the damage of the scale that may cause fatalities occurs, the restoration cost and indirect damage are evaluated. This case is indicated by shade in Table 6.

4) For overtopping waves, it is assumed that no human damage occurs because traffic control is applicable in advance. Since it is difficult to assume blocking materials and their amount by overtopping waves, no restoration cost is evaluated either. Notwithstanding the foregoing, indirect damage inflicted by stones brought over the road surface or road blockage by such stones is estimated, which is indicated by shade in Table 6.

Physical damage to a bridge equivalent to Damage Level I is a fall of superstructure. As the mechanism that may cause a fall of superstructure by an earthquake, three kinds of mechanisms are assumed: dislocation of girder by the damage to bearings or unseating prevention systems, collapse of bridge piers, and dislocation of girder by movement of bridge abutment or bridge pier due to displacement of the foundation. The procedure adopted for bridge damage level judgment is one based on the previous study [2]. A slope disaster that result in Damage Level I occurs when a vehicle on the road is buried under soils. When the collapsed soils by an earthquake or heavy rainfall is estimated to deposit to a height greater than the height of the vehicle window (1m) at the center of a road, the damage level is judged as Level I. In the meantime, there is no case reported where fatalities were involved as a result of settlement of embankment or an approach embankment to a bridge by an earthquake. Therefore no damage designated as Damage Level I is assumed to occur with embankments and bridge approach embankments.

For indirect damage, detour traffic loss is estimated according to the calculation method of traveling cost before and after road work as specified in the Cost-Benefit Analysis Manual by the Ministry of Land, Infrastructure and Transport [3]. To be specific, the traveling cost in ordinary time and that in case one takes a detour in stead of the damaged road section in the event of a disaster are calculated, and the difference between them is regarded as the loss resulting from traffic detour. For this calculation of traveling cost, both the "time cost," which represents the traveling time converted into the monetary value, and "driving cost," which represents all the cost related to traveling of a vehicle, are included. It is also assumed that no change in traffic demand will occur between ordinary time and disaster time. The time cost and driving cost are calculated by using the type-specific traffic volume in the road traffic census, time-value basic unit and traveling cost basic unit in the Cost-Benefit Analysis Manual.

The indirect damage, as occurring from isolation of communities, is estimated as the cost of heliborne transport of support materials including water and food to a community isolated by road damage. Our case study revealed the cases in which communities would lie between suspended road sections without detours and be stranded. However, since such communities have other large-scale communities capable of providing materials and daily life services within their accessible range, the isolated communities that were subject to damage evaluation were not recognized.

As a result of the above damage judgment, 22 cases in terms of a combination of hazards and road facilities were identified as they would induce damage with Damage Level I in principle and are qualified as subjects for risk evaluation, as shown in Table 7. Note that two slopes were judged to suffer Level I damage from both earthquake and heavy rainfall. Thus, 20 were identified as damaged road facilities.

3.3 Risk Evaluation

We performed risk evaluation with the 20 road facilities identified by the damage judgment process in 3.2 above. As an opportunity, we introduced a case in which slope disaster damage to buildings standing along the opposite side of the road is prevented by slope measures. With this opportunity, it is possible to avert occurrence of human damage and restoration cost, i.e., cost for sediment removal and building repair. Site No.19 is the slope where an opportunity emerges.

Table 8 shows a risk register table. A risk is here calculated as the product of likelihood of disaster and magnitude of its consequences. Figure 2 shows a risk curve, which plots the likelihood of disaster to its vertical axis and the magnitude of its consequences to the horizontal axis. On this diagram, a risk located in the top right region is one greater than others outside that region.

Table 7 Number of damaged road facilities

Hazard	Road facility	Damaged facility
Earthquake	Bridge	0
	Embankment	0
	Approach embankment to bridge	0
	Slope	13
	Tunnel	0
Tsunami	Bridge	1
	Embankment	0
	Approach embankment to bridge	0
	Pedestrian bridge	0
Heavy Rainfall	Slope	5
Overtopping	Road	3
Total		22

Table 8 Risk register table

No.	Hazard	Facility	Length (km)	Hazard rating	Threat						Opportunity	
					Human	Resto-ration	Econo-mic	Conse-quence	Risk	Order	Human	Resto-ration
1	Earthquake	Slope	0.1	1	5	1	5	11	11	18	0	0
2	Overtopping	Road	8.9	5	0	0	1	1	5	21	0	0
3	Earthquake	Slope	0.2	1	5	5	10	20	20	8	0	0
4	Earthquake	Slope	0.2	1	5	1	10	16	16	14	0	0
5	Earthquake	Slope	0.4	1	5	5	10	20	20	8	0	0
6	Earthquake	Slope	0.2	1	5	5	10	20	20	8	0	0
7	Earthquake	Slope	0.5	1	5	5	10	20	20	8	0	0
8	Earthquake	Slope	0.2	1	5	1	10	16	16	14	0	0
9	Earthquake	Slope	0.2	1	5	5	10	20	20	8	0	0
10	Earthquake	Slope	0.1	1	5	1	10	16	16	14	0	0
10	Heavy rainfall	Slope	0.1	10	0	1	10	11	110	3	0	0
11	Heavy rainfall	Slope	0.3	10	0	5	10	15	150	1	0	0
12	Heavy rainfall	Slope	0.3	10	0	5	10	15	150	1	0	0
13	Earthquake	Slope	0.3	1	5	5	1	11	11	18	0	0
13	Heavy rainfall	Slope	0.3	5	5	5	1	11	55	4	0	0
14	Heavy rainfall	Slope	0.1	5	5	1	1	7	35	5	0	0
15	Overtopping	Road	1.4	10	0	0	1	1	10	20	0	0
16	Overtopping	Road	1.1	5	0	0	1	1	5	21	0	0
17	Earthquake	Slope	0.6	1	10	10	10	30	30	6	0	0
18	Earthquake	Slope	0.3	1	10	5	10	25	25	7	0	0
19	Earthquake	Slope	0.3	1	10	5	5	20	20	8	10	5
20	Tsunami	Bridge	0.0	1	5	1	10	16	16	14	0	0

For the damage to slopes by earthquakes, although the annual likelihood of event is small, the risk is evaluated high at sites where the human damage and/or the economic loss due to the lack of detour route is large (Site Nos.3, 5-7, 9, and 17-19).

Concerning the damage to slopes by heavy rainfalls, no human damage occurs at the slopes within a precautionary road closure section (Site Nos.10-12), while the annual occurrence likelihood of heavy rainfall is judged to be "likely" because of the local rainfall characteristics at those sites. Eventually, the risks at those slopes occupy the top three in the 22 cases analyzed. Human damage may occur at slopes outside a precautionary road closure section (Site Nos.13 and 14), and the magnitudes of consequences at those sites become rather large. However, since the annual occurrence likelihood of heavy rainfall there is "medium," the risks at these slopes are rated after those at the slopes within a precautionary road closure section.

Site No.20 is a bridge where tsunami is expected. The effected length of road facility or bridge length is shorter than those of damaged slopes, and the resultant human damage and restoration cost are rated small. In addition, as the annual occurrence likelihood of tsunami is "rare," the risk at this site

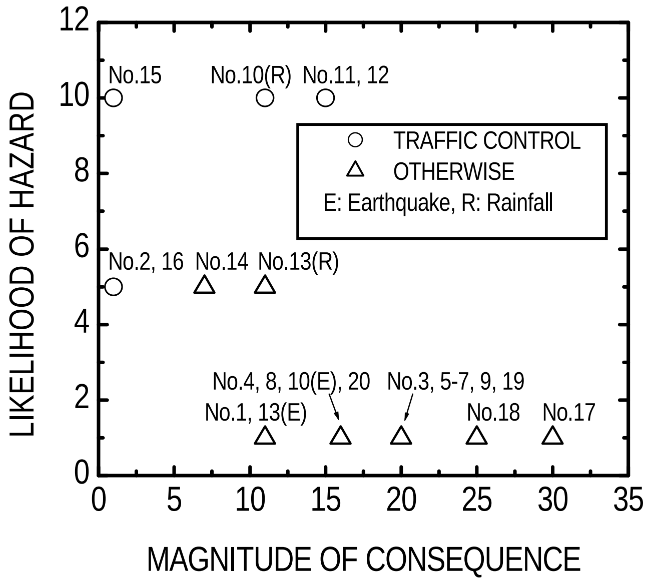

Figure 2 Risk curve

turns out to be small.

For damage to roads by overtopping waves (Site Nos.2, 15 and 16), although likelihood of event is large, the risk at those sites is evaluated to be small. This is because no human damage is judged to occur as traffic control is feasible in advance, and the economic loss there is small as the length of time with traffic blockage is set relatively short, in addition.

Among the road facilities with large risks, the five slopes damaged by heavy rain falls (Site Nos.10-14) rank the top positions and the eight earthquake-damaged slopes (Site Nos.3, 5-7, 9, and 17-19) follow the former. As explained above, plotting the risks for combinations of different hazards and different road facilities on the same risk curve can evaluate the magnitude of risk in a quantitative and integrated manner. One of the features of the risk evaluation conducted in the present study is that the evaluation results are generally more affected by the likelihood of event than its consequences.

3.4 Examination of Road Disaster Prevention Measures

We here introduce an idea that prevention of damage by implementing a road disaster prevention measure is the effect of that measure, define the ratio of measure effect to its cost as the index of cost-effectiveness, and examine the priority of road disaster prevention measures. The cost of measure is approximately estimated by using the previous review on the type of measures and work quantities. At road facilities where opportunity exists such as site No.19, we incorporate the effects of opportunity as well as eliminating the threat into the benefits of road disaster prevention measures.

Slope protection work is effective for the two hazards, i.e., earthquake and heavy rainfall, and the implementation of slope protection work prevents disasters by earthquake and heavy rainfall simultaneously. Thus, for the slopes where the damage levels by both two hazards are rated as Damage Level I (Site Nos.10 and 13), the risks from those two hazards are put together to calculate the measure effects. Within a precautionary road closure section, the basic idea is that human damage resulting from slope damage by heavy rainfall can be prevented. However, since implementing slope protection work will mitigate restoration cost and indirect damage due to heavy rainfall, and is simultaneously capable of reducing earthquake damage, we determined to evaluate the measure effects for those slopes (Site Nos.10-12). Finally concerning the sites affected by overtopping waves (Site Nos.2, 15 and 16), ongoing nonstructural measures or traffic control seems to be sufficient. Therefore, those sites are excluded from a list of sites for examining the priority of road disaster prevention measures.

Table 9 Risk treatment plan

No.	Hazard	Facility	Length (km)	Hazard rating	Conse-quence	Reduced risk (B)	Cost (C) (1,000 yen)	B/C*	Order	Remarks
19	Earthquake	Slope	0.3	1	35	35	1,000	3,500	1	Opportunity
12	Heavy rainfall	Slope	0.3	10	15	150	9,000	1,667	2	
11	Heavy rainfall	Slope	0.3	10	15	150	10,000	1,500	3	
10	Earthquake	Slope	0.1	1	16	16	16,000	788	4	
	Heavy rainfall			10	11	110				
20	Tsunami	Bridge	0.0	1	16	16	3,600	444	5	
8	Earthquake	Slope	0.2	1	16	16	4,000	400	6	
1	Earthquake	Slope	0.1	1	11	11	3,000	367	7	
7	Earthquake	Slope	0.5	1	20	20	7,000	286	8	
13	Earthquake	Slope	0.3	1	11	11	29,000	228	9	
	Heavy rainfall			5	11	55				
14	Heavy rainfall	Slope	0.1	5	7	35	19,000	184	10	
4	Earthquake	Slope	0.2	1	16	16	10,000	160	11	
5	Earthquake	Slope	0.4	1	20	20	13,000	154	12	
17	Earthquake	Slope	0.6	1	30	30	25,000	120	13	
3	Earthquake	Slope	0.2	1	20	20	23,000	87	14	
18	Earthquake	Slope	0.3	1	25	25	32,000	78	15	
9	Earthquake	Slope	0.2	1	20	20	28,000	71	16	
6	Earthquake	Slope	0.2	1	20	20	40,000	50	17	

* B/C=Bx10^5/C

Table 9 shows a risk treatment plan arranged in descending order of cost-effectiveness. It is also possible to rate measure costs according to Table 1, however with this case, measure cost at any site is classified as "minor," and this makes the ranking of cost-effectiveness the same as that of risk. Thus, we adopted the amount of money for estimating the measure cost in Table 9.

The effect of road disaster prevention measures at site No.19 becomes larger by including the opportunity compared with the case where threat alone is considered. However according to Table 9, it seems that the cost-effectiveness of the road disaster prevention measures for Site 19 is highly evaluated because of the small measure cost rather than the impact of the opportunity. Similarly, a high score is given to the cost-effectiveness at site No.20, where the tsunami is expected to cause damage to the bridge, because of the small measure cost.

At site Nos.10 and 13, which are slopes where damage is expected by two hazards, i.e., earthquake and heavy rainfall, the road disaster prevention measures have larger effect by considering prevention of the two hazards rather than prevention of either single hazard. At the three slopes damaged by heavy rainfall (Site Nos.10-12) including the above site No.10, although the measure cost is relatively high, the risk is rated large, which eventually leads to higher evaluation of the cost-effectiveness of the road disaster prevention measures.

4. CONCLUSION

We proposed a practical procedure to systematically evaluate damage risks to road facilities by natural disasters and conducted a case study for an actual road section. The proposed procedure particularly focuses on quantitative evaluation of risks to various road facilities from various disasters by using the common indices, and incorporates both threats and opportunities, which are favorable outcomes incidentally resulting from implementation of road disaster prevention measures, into analysis. Based on the idea that prevention of damage by implementing road disaster prevention measures is effectiveness of measures, we examined the priority of measures from the viewpoint of the ratio of the measure effects to its cost.

Although further detailed study will be necessary for examining the rating of hazard likelihood

and its consequences, which are introduced to make quantitative evaluation of risks in our study, we believe that the proposed procedure will be helpful in prioritizing road disaster prevention measures by comparing the impacts of various disasters on various road facilities.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to all the parties that provided valuable data for conducting the case study.

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